

The Radio Outburst from η Carinae

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Abstract. η Carinae is in the midst of a radio outburst which has made it one of the brightest stellar radio sources in the sky. This paper reviews our current understanding of this outburst, and discusses how the radio emission may be used to study the mass loss history of η Car in very recent history (tens of years).

1. Radio Observations of η Carinae

η Carinae has proven to be as remarkable a radio source as it is in nearly every other wavelength range. This paper reports on observations of η Car made since 1992 with the Australia Telescope (ATCA) at frequencies from 1.4 to 9 GHz, which reveal an extraordinary outburst in which the radio emission from hot ionized gas within several arcseconds of the star has increased fourfold in several years. Unfortunately we do not have a long time history of the behaviour of the radio flux from η Car from which to judge the significance of the current outburst. The reason for this is largely technical: until the early 1990s, there have been no telescopes in the southern hemisphere capable of separating the flux of η Car from that of the surrounding large and radio-bright Carina Nebula at the higher microwave frequencies required to study the core region around the star. While both the Fleurs (1.4 GHz; Retallack 1983) and Molonglo (0.843 MHz; Jones 1985, Whiteoak 1994) radio synthesis telescopes were able both to separate the η Car radio source from the Carina Nebula and to estimate the size of the radio source (e.g., Whiteoak 1994 measured a flux of 1.1 ± 0.1 Jy with a size of $50'' \times 15''$ at 0.843 GHz), it turns out that the radio flux at these lower frequencies consists partly of thermal emission from the Homunculus nebula around the star and the core region around the star itself, which has a spectrum rising with frequency, and partly of nonthermal emission (with a

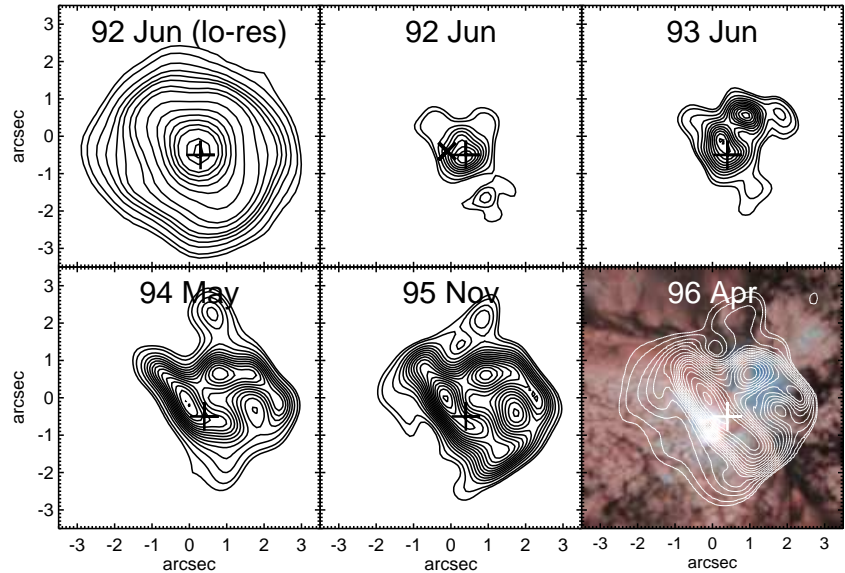


Figure 1. The evolution of the morphology of the radio emission from the core of η Car. The upper left panel is a conventional CLEAN image with a restoring beam size of $1.0''$. The other images are deconvolved using maximum-entropy reconstruction and then restored with an $0.3''$ beam. In final panel (96 April), the HST/WFPC2 image is used as a background. In each panel the plus symbol denotes the location of the “radio star”.

falling spectrum) from the outer ejecta of the star, and the resolution of these low-frequency telescopes is not adequate to distinguish between these different components. ATCA observations show that the east–west extension of the source size measured by Molonglo is due to the nonthermal contributions of the “S” condensation to the west of the star, and the “E” condensation to the east. At these low frequencies much of the Homunculus is optically thick and the large radius of this optically thick surface prevents us from seeing any details in the volume immediately surrounding the star, and further means that the outburst occurring close to the core has little effect on the low-frequency radio fluxes.

At higher microwave frequencies the Homunculus is more transparent. The initial higher-frequency observations of η Car with the ATCA in 1992 June were reported by White et al. (1994). These were made at the highest frequency available, 9 GHz, in order to achieve the highest possible spatial resolution, nominally $\sim 1''$. The observations showed a strongly centrally peaked compact source surrounded by a symmetrical radio nebula of dimension several arcseconds (Fig. 1, upper left panel). The symmetry axes of the nebula matched those of the Homunculus well. The total flux was 0.7 Jy at 9 GHz.

In subsequent radio observations the flux of η Car was observed to increase dramatically, and a monitoring campaign was initiated (Duncan et al. 1995). The time evolution of the 8.6 GHz radio flux from η Car is shown in Figure 2. The radio flux of η Car is so strong that we can make reliable images of it at a spatial

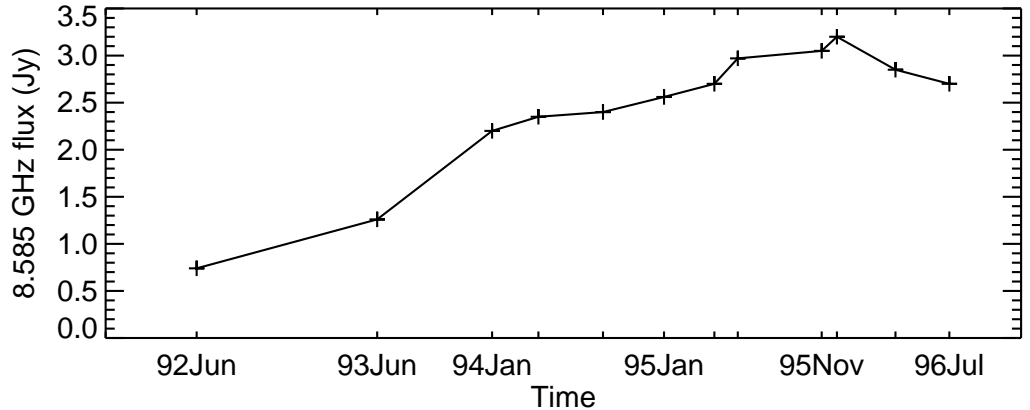


Figure 2. The time evolution of the radio flux from η Car at 8.585 GHz since ATCA observations began in 1992.

resolution which is somewhat better than nominal: effectively, we can sacrifice some of the dynamic range available in the data in order to improve resolution. We use such “super-resolved” images to study changes in the central core of the radio source. The second image in Fig. 1 (upper middle panel) shows an image made from the same data as the first panel, but using maximum entropy deconvolution and a restoring beam of $0.3''$. The strong central peak is shown to be extended at this resolution, with weaker projections to the north–west and north–east.

The next 4 panels show how the appearance of new flux is associated with spatial changes in the radio source. Initially (93 June) a bright compact feature appears $1''$ to the north–west of the “star”, and there is some extension from the the “star” to the north–east. As the outburst develops, strong emission appears in a narrow ridge aligned from the north–east to the south–west, roughly orthogonal to the polar axis of the Homunculus, while other features appear to the north–west of this ridge. The peak brightness temperatures in these images are close to 10^4 K, consistent with optically–thick thermal emission from photo-ionized gas. None of the features in the images show motion consistent with them being clumps ejected by the star since 1992, so they must have been present in their current locations at the onset of the outburst.

An important and unresolved question in this analysis is the exact location of the star in the radio images. We have argued, based on the symmetry evident in the first panel of Fig. 1 and the strong compact central peak in the high–resolution data (upper middle panel), that the star is at the location of the plus symbol shown in Fig. 1, to an accuracy of order $0.1''$. However, the best position for the optical star (based on astrometrical analysis of HST images using stars present on the same chip as η Car for reference, kindly provided by D. Ebbets) is about $0.5''$ east of this position (shown as an \times in the upper middle panel of Fig. 1). In principle radio positions can be extremely accurate, since they are referenced to a frame of background extragalactic radio sources whose positions are known self–consistently down to microarcseconds. However, at the time of the 92 June observation the position of our positional–reference source was not accurately known, and there is some doubt about the accuracy of the baseline

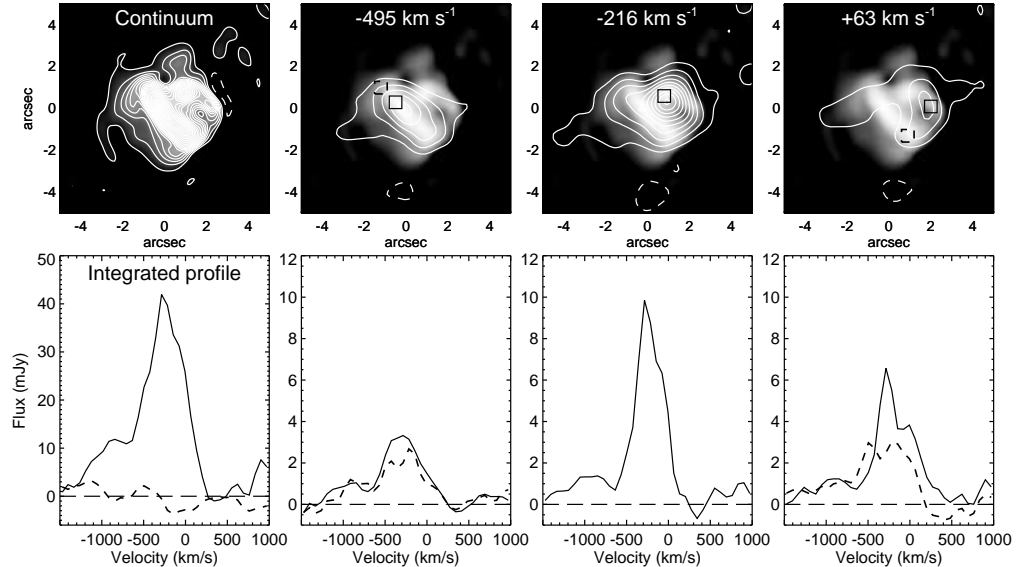


Figure 3. Velocity information from the H91 α recombination line in 96 April. The leftmost set of panels shows the continuum image (upper) and the integrated line profile (below, with a noise profile for comparison). The other panels show images at sample velocities (upper, contours, overlaid on greyscale continuum image) and (lower) spectra at locations corresponding to the small boxes in the upper panels.

lengths during this observation which affects our confidence in the positional accuracy for this epoch. Unfortunately, in subsequent epochs the “radio star” is not readily identifiable in the images. However, based on the correspondence between successive epochs we do not believe that the radio position (10 45 03.55, -59 41 04.04) is consistent with the HST position (10 45 03.615, -49 41 03.96). The radio–optical overlay on the last panel of Fig. 1 is based on aligning the bright radio “ridge” with where we guess the equatorial disk to be in the optical image, and is therefore uncertain.

We have regularly observed the H91 α recombination line at 8.585 GHz since June 1993. These are difficult observations since the very weak line must be separated from a strong continuum whose spectrum varies with location. There have been changes in the line spectrum (Duncan et al. 1995), but for most of the outburst the line has been very broad, nearly exclusively blue-shifted and centered near -250 km s^{-1} (Fig. 3), whereas the star is at -16 km s^{-1} (LSR). Note that the radio emission suffers no scattering and therefore the measured velocities should correspond to the motion of the emitting gas, unlike the velocities of optical lines which may be altered by the motion of scattering dust grains. There does seem to be some weak emission out to -1000 km s^{-1} consistently present in the data. Although there is a weak trend for the most blue-shifted gas to be to the east and the most red-shifted gas to be to the west, there are no very strong patterns in the velocity structure: the line appears to be very broad along all lines of sight.

2. Summary

Based on the data available, we attribute the outburst to the ionization of a large mass of previously neutral gas in the outflow from the star. The fact that we see predominantly blue-shifted emission to the north-west of the star suggests that it lies in the equatorial skirt between us and the star, rather than in the north-eastern lobe on the other side of the star. The ridge-shaped feature in Fig. 1 may represent the inner portion of the equatorial skirt seen nearly edge-on. The large density of gas in the outflow from η Car can produce recombination close to the star, so that the bulk of the outflow is neutral and is only revealed when ionized by an as yet unknown agent. We note that the timing of the outburst onset is close to the time of the last “shell episode” identified by Damineli (1996) in which high-excitation lines vanish, presumably because the effective radius of the photosphere increases dramatically and the effective temperature falls. However, we have not yet identified a direct physical causal relationship for an association of the radio outburst with the shell episodes, which apparently cause a sharp drop in the ionizing flux followed by a restoration to previous levels, rather than an increase in the ionizing flux as we require. Assuming that a pulse of ionizing flux originated close to the star and proceeded outwards, the new sources appearing in the radio images represent the densest clumps in the outflow of η Car and the sequence in which they appeared at least partially reflects their distance from the star. Thus the newly ionized material reveals some of the recent history of η Car’s outflow. If all the neutral gas within a certain radius has been ionized, then the radio images indicate a large degree of inhomogeneity in the outflow. In particular, the absence of red-shifted radio emission is puzzling since the line of sight to the far side of the equatorial disk seems to be optically thin. We note that there have been no reports of an increase in the optical recombination line fluxes (such as $H\alpha$) which would be expected to accompany the observed radio emission, but this can possibly be explained by the effect of obscuration at visible wavelengths.

Acknowledgments. This work was supported by NSF grants AST 92-17891 and INT 95-13340. The Australia Telescope is funded by the Commonwealth of Australia for operation as a National Facility managed by CSIRO. We thank Dennis Ebbets for kindly providing the position of the optical peak.

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